

Outage probability due to Stimulated Raman Scattering in  
GPON and TWDM-PON coexistence

*Original*

Outage probability due to Stimulated Raman Scattering in GPON and TWDM-PON coexistence / Curri, Vittorio; S., Capriata; Gaudino, Roberto. - ELETTRONICO. - 2014:(2014). (Intervento presentato al convegno OFC 2014 tenutosi a San Francisco nel 9-13 Marzo 2014).

*Availability:*

This version is available at: 11583/2542693 since:

*Publisher:*

OSA Optical Society of America

*Published*

DOI:

*Terms of use:*

openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)

# Outage probability due to Stimulated Raman Scattering in GPON and TWDM-PON coexistence

V. Curri<sup>(1)</sup>, S. Capriata<sup>(2)</sup> and R. Gaudino<sup>(1)</sup>

<sup>(1)</sup> DET, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129, Torino, Italy. gaudino@polito.it

<sup>(2)</sup> Telecom Italia, Via G. Reiss Romoli 274, 10148, Torino, Italy. stefano.capriata@telecomitalia.it

**Abstract:** TWDM-PON (ITU-T G.989) may induce relevant extra-attenuation on coexistence with GPON due to Raman nonlinearity. We give a compact theoretical framework to study this problem considering polarization statistical effects, leading to outage probability characterization.

**OCIS codes:** 060.2330 Fiber optics communications; 290.5910 Scattering, stimulated Raman;

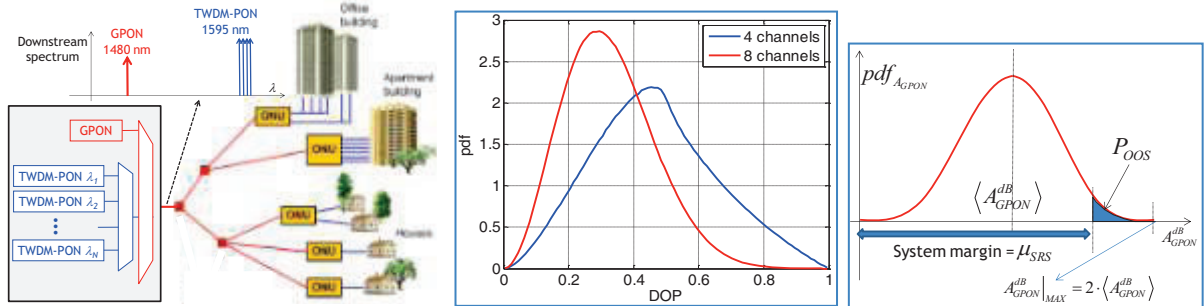
## 1. Introduction

ITU-T is currently releasing the new standard for NG-PON2 under Recommendations G.989 and acronym TWDM-PON [1]. As schematically shown in Fig. 1, *left*, and focusing on the downstream (DS) only, 4  $\lambda$ 's (with envisioned upgrades to 8) are used in the L-band (just below 1600 nm, 100 GHz spacing): an allocation allowing complete backward compatibility with previous PON standards, including GPON, XG-PON and RF-Video. Anyway, Stimulated Raman Scattering (SRS) may become detrimental in these “full compatibility” scenario. As shown in [2], if the TWDM-PON channel power is above a given threshold, SRS becomes critical for GPON, because GPON acts as a Raman pump for the TWDM-PON channel comb, transferring optical power from GPON to TWDM-PON. Consequently, GPON may experience relevant power depletion because the SRS presents maximum efficiency [3] at the spectral separation of about 100-110 nm from GPON (1490 nm) to TWDM-PON. After detailed time-domain numerical simulations, we showed in [2] that the walk-off among channels induced by the chromatic dispersion is sufficiently fast (due to the large spectral separation) to average out any time-dependent effects on GPON, so that the SRS-induced GPON depletion can be simply accounted for as an extra-loss, named  $A_{GPON}$ , that depends on TWDM-PON power level. Hence, given the maximum tolerable  $A_{GPON}$ , we have a limit on the maximum admissible TWDM-PON power level. Moreover, very simple analytical formulas can be derived to estimate it, making use of literature results originally developed 10 to 15 years ago to assess functioning of distributed Raman amplifiers [3,4].

In this work, we show that, due to the fiber Polarization Mode Dispersion (PMD),  $A_{GPON}$  is actually not deterministic, but it turns out to be a random process. Its properties depend on several polarization parameters, and specifically on the link PMD given by the fiber  $\delta_{PMD}$  [ps/sqrt(km)] and on the degree of polarization (DOP) [7] of the TWDM-PON channel comb. The main novelties of this work are in particular the following:

- we extend the analysis presented in [2] to include random polarization-related effects;
- we fully characterize the resulting  $A_{GPON}$  probability density function (pdf);
- we evaluate the resulting out-of-service probability induced by  $A_{GPON}$  exceeding a given system margin.

For fibers with  $\delta_{PMD}$  above 0.1 [ps/sqrt(km)] and/or for  $DOP=0$ , we show that the depletion  $A_{GPON}$  is deterministic and can be modeled by results presented in [2]. Typical system scenarios are indeed characterized by  $\delta_{PMD}<0.1$  [ps/sqrt(km)] and random  $DOP$ , consequently  $A_{GPON}$  must be accounted for as random. It worsens performances compared to the deterministic case and, given the maximum tolerable out-of-service probability on the GPON, the maximum admissible TWDM-PON power level must be further reduced of up to 3 dB.



**Fig. 1: Left:** The considered system scenario characterized by full-coexistence of GPON and TWDM-PON. **Center:**  $DOP_{TWDM}$  pdf for  $N_{TWDM}=4$  and 8. **Right:** qualitative description of the  $A_{GPON}$  probability density function and the related  $P_{OOS}$ .

## 2. Theory of polarization dependent SRS depletion on GPON.

We consider the scenario described in Fig. 1, *left*, for DS only, where a GPON coexists with  $N_{TWDM}$  TWDM-PON  $\lambda$ 's. Let  $P_{GPON}$  and  $P_{TWDM}$  be the launched power levels per channel. In [2], to simplify the analytical treatment, we assumed that the polarization scrambling induced by PMD along the fiber was large enough to induce complete polarization-averaging, so that SRS becomes completely depolarized and thus deterministic. Anyway, from the extensive literature on Raman distributed amplifiers [4] results that, under most common conditions [4], polarization statistics are relevant, leading to random gain in Raman amplifiers or, in our case, random GPON depletion  $A_{GPON}$ . Physically, it is caused by SRS being most efficient for co-polarized signals, and almost null for orthogonal polarized signals [3]. Due to fiber PMD, the relative state of polarization (SOP) of two  $\lambda$ 's changes randomly along the fiber, with a correlation length that decreases vs. PMD and spectral separation. Since PON links are limited to 20-40 km and typically fibers are SMF with  $\delta_{PMD} < 0.1$  [ps/sqrt(km)], we use the following simplifying assumptions.

- The relative SOP's of the  $N_{TWDM}$  TWDM-PON  $\lambda$ 's remain stable along the full PON fiber link, being the TWDM-PON overall spectral width of the order of a few hundreds of GHz, and so relatively narrow. Thus, the resulting global DOP of the TWDM-PON channel comb is constant with length and equal to the value  $DOP_{TWDM}$  set at the transmitter. For our purposes, we can identify the entire TWDM-PON comb as an equivalent single optical source with an average power  $N_{TWDM} \cdot P_{TWDM}$  and a given  $DOP_{TWDM}$ . If all lasers are polarization aligned, we have  $DOP_{TWDM} = 1$  while if they are alternatively orthogonal we have  $DOP_{TWDM} = 0$ .
- On the contrary, the relative SOP between GPON and TWDM-PON changes quickly along the fiber link, due to the very large spectral separation (more than 100 nm), and follows a statistics determined by PMD

Reusing distributed Raman amplifier theory, we can adapt to the PON scenario the results derived in [4], from which the differential equation determining the evolution with distance  $z$  of the GPON power  $P_{GPON}$  in the fiber is:

$$\frac{\partial P_{GPON}}{\partial z} = -\frac{\alpha_{dB}}{10 \log_{10}(e)} P_{GPON} - N_{TWDM} C_R P_{TWDM} \{1 + DOP \cdot [\hat{s}_{GPON}(z) \cdot \hat{s}_{TWDM}(z)]\} P_{GPON} \quad (1)$$

where  $\alpha_{dB}$  is the fiber loss coefficients in [dB/km],  $C_R$  is the polarization average Raman efficiency at the GPON-to-TWDM-PON spectral distance (for SMF,  $C_R \approx 0.3$  1/W/km) and  $\hat{s}_{GPON}(z)$  and  $\hat{s}_{TWDM}(z)$  are the GPON and TWDM-PON Stokes vectors [5] randomly evolving with distance  $z$ . From Eq. (1) and adapting the theory in [4], it is straightforward to derive the solution of Eq. (1) giving the GPON depletion, in useful dB unit. Its expression is:

$$A_{GPON}^{dB} = [10 \log_{10}(e)] \cdot C_{R,max} \cdot N_{TWDM} \cdot P_{TWDM} \cdot L_{eff} \cdot \{1 + \eta \cdot DOP_{TWDM}\} \quad [dB] \quad (2)$$

where  $L_{eff}$  is the fiber effective length given by  $L_{eff} = \frac{10 \log_{10}(e)}{\alpha_{dB}} \cdot \left(1 - 10^{-\frac{\alpha_{dB}}{10} L}\right)$ ,  $L$  is the fiber length in km, while  $\eta$  is a key parameter for the presented theory, corresponding to the following polarization-dependent random variable:

$$\eta = \frac{1}{L_{eff}} \int_0^L 10^{-\frac{\alpha_{dB}}{10} z} [\hat{s}_{GPON}(z) \cdot \hat{s}_{TWDM}(z)] dz \quad (3)$$

In [4], it has been demonstrated that  $\eta$  is a truncated-Gaussian random process in  $[-1;1]$  with an analytical closed form for the variance depending only on  $\delta_{PMD}$  and  $L$  that approaches zero for large values of  $\delta_{PMD}$ . Hence, Eq. (2) shows that the GPON depletion is a random process depending on  $DOP_{TWDM}$  and  $\eta$ , with average value corresponding to the “deterministic” results presented in [2], whose expression is:

$$\langle A_{GPON}^{dB} \rangle = [10 \log_{10}(e)] \cdot C_{R,max} \cdot N_{TWDM} P_{TWDM} \cdot L_{eff} \quad [dB]. \quad (4)$$

Thus, Eq. (2) can be rewritten as:  $A_{GPON}^{dB} = \langle A_{GPON}^{dB} \rangle \cdot \{1 + \eta \cdot DOP_{TWDM}\}$ . Considering that  $DOP_{TWDM}$  can only range in  $[0,1]$  and  $\eta$  varies in  $[-1;1]$ , we have that  $A_{GPON}^{dB}$  may assume random values from 0 to  $2 \cdot \langle A_{GPON}^{dB} \rangle$ , as qualitatively shown in Fig. 1, *right*, and practical effects are the key-issue of the present work. In general, if  $DOP_{TWDM}$  is given,  $A_{GPON}^{dB}$  is a truncated Gaussian random variable whose maximum value it may assume is 2 times (in dB) its average value. The knowledge of its exact statistics is therefore fundamental in evaluating loss budgets. Its variance is given by  $\eta$  that is fully characterized in [4], but it also depends on  $DOP_{TWDM}$ . To have a comprehensive statistical characterization, we assumed that the relative SOP of the TWDM-PON channels is completely random, as it practically happens if the  $N_{TWDM}$  TWDM-PON line cards are joined using SMF. So,  $DOP_{TWDM}$  is a random process as well, and its pdf can be derived, as shown in Fig. 1, *center*, for  $N_{TWDM} = 4$  and 8. Then, using the properties of the product of two random processes [6] in Eq. (2), we were able to find the exact  $A_{GPON}^{dB}$  pdf and to use it in defining system parameters.

### 3. The outage probability due to the SRS-induced GPON extra loss.

In dimensioning the loss budget for GPON, a system margin  $\mu=2$  dB is allocated according to all ITU-T Recommendations. Considering the depletion problem presented in this paper, it is reasonable to assume to allocate no more than  $\mu_{SRS}=1$  dB to the SRS-induced GPON extra loss. Therefore, in case the random  $A_{GPON}^{dB}$  exceeds  $\mu_{SRS}$ , the GPON can experience an out-of-service (OOS) situation whose prospect is given by the *outage probability*  $P_{OOS} = p\{A_{GPON}^{dB} > \mu_{SRS}\}$ , as qualitatively described in Fig. 1, *right*. Thanks to the analytical tools outlined in Sec. 2, we can evaluate  $P_{OOS}$  calculating the integral of the  $A_{GPON}^{dB}$  pdf above  $\mu_{SRS}$ . In Fig. 2, *left*, we show the resulting *outage probability* vs.  $P_{TWDM}$  for  $L=40$  km, variable PMD and  $N_{TWDM}=4$  or 8.  $P_{OOS}$  grows with  $P_{TWDM}$  increasing and with  $\delta_{PMD}$  decreasing. The latter property is somehow unusual, because, typically, mitigation of propagation impairments requires low PMD, while for the SRS-induced extra loss the larger the PMD, the lower the impairment. In particular, for  $\delta_{PMD} \geq 0.1$  [ps/sqrt(km)], it turns out that the polarization averaging is sufficiently high so that  $A_{GPON}^{dB} \cong \langle A_{GPON}^{dB} \rangle$ , i.e., the same performance we would obtain for  $DOP_{TWDM}=0$ , and the problem becomes almost deterministic, so that the system is out of service if the average extra loss given in Eq. (4) is above  $\mu_{SRS}$ . Anyway, for  $\delta_{PMD} < 0.1$  [ps/sqrt(km)], as it happens for most modern links, for which  $\delta_{PMD}$  is often below 0.04 [ps/sqrt(km)],  $A_{GPON}^{dB}$  can assume values higher than its average with a non-negligible probability. The graph in Fig. 2, *left*, shows that, if we fix a maximum tolerable outage probability  $P_{OOS,max}=10^{-5}$ , this determines maximum  $P_{TWDM}$  values that depend on  $\delta_{PMD}$ , which is plotted in Fig. 2, *right*, for  $L=20$  and 40 km, and for  $N_{TWDM}=4$  and 8.

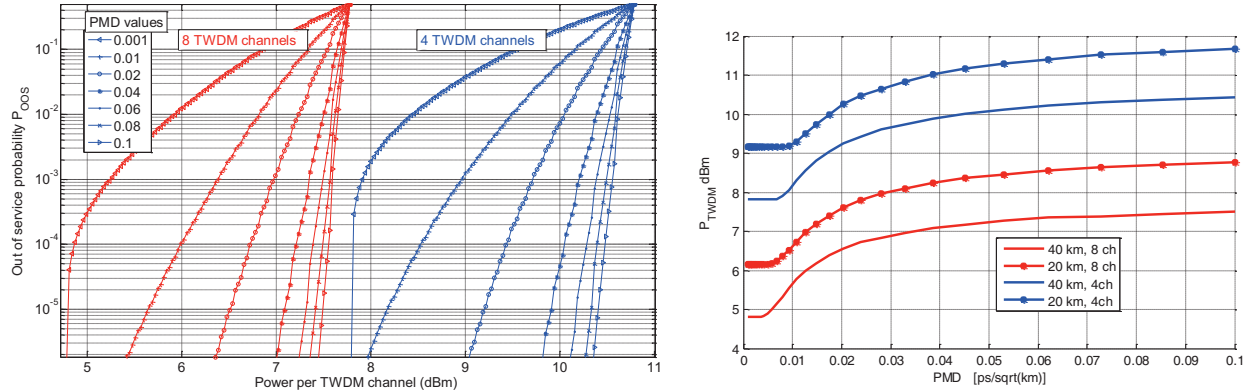


Fig. 2: left:  $P_{OOS}$  vs.  $P_{TWDM}$  for different values of  $\delta_{PMD}$  for  $L=40$  km, for  $N_{TWDM}=4$  and  $N_{TWDM}=8$ .

Fig. 2: right:  $P_{TWDM,max}$  vs.  $\delta_{PMD}$  for  $L=20$  km and  $L=40$  km, and for  $N_{TWDM}=4$  and  $N_{TWDM}=8$  for  $P_{OOS,max}=10^{-5}$ .

Fig. 2, *right*, is the most important result of this work, showing the maximum admissible  $P_{TWDM}$  that gives a 1 dB depletion on GPON with probability below  $10^{-5}$ , and can be used to dimension next-generation TWDM-PON systems. It shows that for very low PMD ( $\delta_{PMD} \approx 0$ )  $P_{TWDM}$  should be dimensioned 3 dB below the value reliable for high PMD links, which turns out to be equal to the reliable  $P_{TWDM}$  in case  $DOP_{TWDM}=0$ . By looking at the actual values of max  $P_{TWDM}$ , we note that the SRS impairment can be really significant. In particular, for  $N_{TWDM}=8$  and  $L=40$  km, we have that  $P_{TWDM}$  should be below 7.5 dBm for high PMD, and even below 4.5 dBm for very low PMD. Even for  $N_{TWDM}=8$  and  $L=20$  km,  $P_{TWDM}$  cannot exceed 11 dBm for very low PMD fibers ( $\delta_{PMD} < 0.04$  [ps/sqrt(km)]).

### 4. Comments and conclusions:

We propose an analytical original characterization of the SRS-induced GPON extra loss due to TWDM-PON. We showed that such an effect may induce an hard limit to the maximum power on TWDM-PON channels, as low as 7.5 dBm/channel in case of  $N_{TWDM}=8$  and  $L=40$  km with high-PMD links. While the use of typical low-PMD modern fibers may require up to 3 dB further reduction on admissible power levels. This problem worsens in case also the RF-video and XGPON wavelengths are present, and worsens even more if a WDM-overly is added in the L-band.

**Acknowledgements:** This work was supported by Telecom Italia.

### References

- [1] Yuanqiu Luo *et al.*, "Time- and Wavelength-Division Multiplexed...", JLT **4**, 587-593 (2013).
- [2] R. Gaudino *et al.*, "Propagation impairments due to Raman ...", ECOC 2013, Paper P.6.19

- [3] Y. R. Shen, *Principles Of Nonlinear Optics*, Wiley-Interscience, New York, (1984)
- [4] E. S. Son *et al.*, "Statistics of Polarization-Dependent Gain in Fiber Raman Amplifier," JLT **23**, 1219-1226 (2005).
- [5] T. Okoshi, K. Kikuchi, *Coherent Optical Fiber Communications*, D. Reidel Publishing (1988)
- [6] M. Springer, *et al.*, "The distribution of products of independent random variables". SIAM Journal on Applied Mathematics **14** (1966)